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Black carbon emissions from trucks and trains in the Midwestern and Northeastern United States from 1977 to 2007

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HIGHLIGHTS

- BC emissions from trucks and rail have decreased between 1977 and 2007.
- These decreases are noted despite large growth in the volume of freight shipped.
- Regulatory efforts to decrease BC emissions from trucks has been largely successful.
- Historically the fabricated metal industrial sector has dominated BC emissions.
- However, clustering of transportation results in smaller decreases in urban centers.

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ABSTRACT

We have developed a framework to estimate BC emissions from heavy-duty diesel trucks and trains engaged in transporting freight in the Midwestern and Northeastern United States (MNUS) from 1977 to 2007. We first expand on a previous development of a regional econometric input–output model (REIM) that has been used to estimate commodity flows between 13 states in the MNUS (plus the rest of the US) and 13 industrial sectors. These commodity flow data are then distributed over the MNUS using a stylized link-and-node network, which creates great circle transportation links between nodes in each state at the county with the largest population. Freight flows are converted to BC transportation emissions and the resulting BC emissions are compared to the MACCity BC emissions inventory. We find that from 1977 to 2007 potential emission growth from the continued increase in freight tonnage in the MWUS is counteracted by decreases in the BC emission factor of heavy-duty diesel trucks, which results in an overall decrease of BC emissions by 2007. One sector (fabricated metal product manufacturing) has dominated the BC transportation emissions throughout 1977 to 2007 with transportation emissions remaining relatively unchanged from 1977 to 1997 and then decreasing out to 2007. The BC transportation emissions are concentrated in and around the urban centers, which serve as transportation and production nodes for industrial manufacturing. Our BC emissions are distributed along stylized transportation corridors that are not well represented in emissions inventories that largely distribute emissions via a population proxy. The framework established in this study can be used to estimate future BC transportation emissions under a set of stylized economic, technological, and regulatory scenarios.

1. Introduction

Black Carbon (BC) aerosols influence both air quality and the global climate; they are a human health hazard (e.g. Janssen et al., 2012) with a net radiative forcing on the order of 1 W m^{-2} of which nearly one-third is attributed to fossil fuel combustion (Bond et al., 2013). In industrialized nations, including the US where biomass combustion (i.e. cooking and heating stoves) emissions are relatively low, on-road heavy duty diesel vehicles (HDDVs) in the transportation sector are the dominant source of BC emissions

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(Bond et al., 2013). The transportation sector in the US has transformed dramatically since the 1970s: freight volumes have nearly tripled, increasing at a rate that is faster than the growth of US Gross National Product (GNP) (US DOT, 2013); emission factors for BC from HDDVs, which account for over 50% of US BC transportation emissions (US EPA, 2012a), have declined by nearly 80% (US EPA, 2012a; US EPA, 2012b); and the transportation sector has transformed as a part of an increasingly interconnected global economy that is dependent on just-in-time deliveries of both intermediate and finished commodities (Donaghy, 2012).

The ultimate impact of an increased demand for transportation and a concurrent decrease in BC emission factors on the total BC emissions is complicated. This paper examines the factors by which freight flows impact BC emissions in the Midwestern and Northeastern US (MNUS) over a historical period (1977–2007) in order to determine and describe the major factors that impact the overall trend. We use a regional econometric input–output model (REIM) to derive time series on commodity flows in value terms, which we convert to freight flows in weight terms. Then, distributing the derived freight flows by mode of transport in a stylized transportation network, and employing available historical emission factors for HDDV and rail, we estimate gridded BC emissions. Our methodology allows us to isolate the BC emissions that result from the individual influences of economic and regulatory forces. This framework provides us with the capability to examine future BC emissions under a variety of economic and regulatory scenarios.

There have been many factors influencing BC emissions from freight transportation in the MNUS from 1977 to 2007. The majority of BC emissions from the transportation sector come from the HDDV fleet with a minor contribution from the rail fleet (ICF, 2005). The transportation of freight by HDDVs and rail is controlled by demand from producers and consumers of finished and semi-finished products, which themselves are driven by underlying dynamics of both regional and global economies including growth, supply and demand, and globalization. At the same time, particulate matter (PM) emissions, including BC emissions, have been subject to increasingly stringent regulatory efforts from the US EPA (US EPA, 2012a) and from local and regional municipalities (e.g. NYSDEC, 2014).

From 1977 to 2007 the value of all freight movement in the US has grown at an annual rate of roughly 5%, which is more than twice as fast as the growth of the country's Gross National Product (GNP) (US DOT, 2013). Much of the increase in demand for freight shipment is the result of aggregated economic growth as well as changes in the structure, connectivity, and infrastructure of industrial producers, which is often referred to as the geography of production (e.g. Feenstra, 1998; Donaghy, 2007). In addition, the transportation sector has experienced advancements in information technologies, which has increased the efficiency and reliability of the freight transportation sector. This has resulted in a transition to "just-in-time" inventory management systems where products and materials can be shipped quickly in an "on-demand" basis (e.g. Krishnamarthy, 2007) with a growing trend towards regular shipments of unfinished goods between production centers throughout the production process (Castells, 2000). Subsequently the industrial production process has grown more dependent upon the transportation sector. Essentially, industries have taken advantage of regional economies of scale (Feenstra, 1998) and economies of scope (Jones and Kierzkowski, 2001), which has resulted in a "hollowing out" (or a reduction of local purchasing by firms) and "clustering" (or agglomeration of similar types of activities) of production and transportation nodes (Munroe et al., 2007) as industries move their production processes to locations that maximize advantages from economies of scale. This results in, for instance, factories and production centers that may have been previously distributed throughout the region to gather in and around the most efficient transportation nodes (i.e. urban centers). An example is the regular transportation of unfinished automobile parts between Canada and the US (Anderson and Coates, 2010), where car parts experience multiple border crossings throughout the production process (Anderson, 2012). This is a significant change from the traditional vertically integrated or traditional assembly line production process (Feenstra, 1998).

At the same time, the US EPA and regional municipalities have become increasingly aware of the negative health effects of BC emissions (e.g. Anenberg et al., 2012) and have indirectly promulgated increasingly stringent controls on BC by continuously tightening the National Ambient Air Quality Standard (NAAQS) for all particulate matter (PM) (US EPA, 2012a, 2012b, 2013). This regulatory tightening, combined with a continued increase in technological efficiencies in transportation technologies, has resulted in the HDDV emission factor for BC to drop from 1.29 μg/g of fuel in 1977 to 0.39 μg/g in 2007 (from the US EPA MOVES software, US EPA, 2012b). This downward trend in BC emission standards is expected to continue into the future. Data on the emission factor of BC from the private rail industry are limited.

This study examines the connection between regional BC emissions and regional economic activities through model representations of the individual behavior of sectors within the MNUS. The MNUS has a large population clustered in urban centers with high manufacturing and transportation volumes among a small enough number of states to keep the computational intensity at reasonable levels. This regional focus also allows for a more complete representation of the regional activities that other inventories with global spatial coverage are often unable to capture. Instead of distributing emissions based on a population proxy, as is common practice in a number of standard emission inventories (e.g. Bond et al., 2004, 2007; Lamarque et al., 2010) we distribute emissions based on an stylized transportation network that allows us to examine sub-regional impacts of the transportation sector on BC air quality. We compare our methodology to other existing BC emissions inventories and explore the strengths and weaknesses of our derived BC emissions. The framework created through the development of the REIM and in this work allows for the direct estimation of future BC emissions under a variety of economic, technological, and regulatory scenarios through changes in transportation patterns and emission factors.

We attempt in this paper to answer two primary questions: (1) What has the BC emissions trend been from HDDV and rail transportation sources between 1977 and 2007 and what are the major factors that have driven that trend? (2) What economic sectors dominate these BC emissions and what major changes have occurred from 1977 to 2007? Our analysis focuses primarily on the overall processes driving spatial and temporal BC emissions over the historical period. Section 2 describes the methodology of this study, including details of the derivation of the necessary commodity-flow data, their conversion to freight-flow data, and the process by which they are distributed by mode and transport network, and the format and caveats of the resultant BC emissions. Section 3 evaluates these BC emissions against an existing BC emission inventory. Section 4 explores the implications of these BC emissions including the interaction between increasing freight volume and decreasing emission factors, the major contributing sectors and their trends, and the regional impact of BC emissions in the Midwestern and Northeastern US.

2. Methods

In this section we detail the process and steps taken to estimate a time series of gridded BC emissions from both HDDV and rail

($BC_{HDDV+Rail}$) transport using economic and industry data from 1977 to 2007 (see Fig. 2). We are concerned in this study with the physical effects of commerce in the form of freight flows between 13 industrial sectors (Table 1) located in 13 states in the MNUS (Fig. 1) and the rest of the US (RUS). In order to produce data on freight flows in our domain, it is necessary first to possess a time series of inter-state and inter-industry commodity flows for each industry in each state for each year. Unfortunately, annual data on such commodity flows are not available and thus must be derived from other reported data for the period of interest. In order to derive the necessary commodity-flow data, we formulate and estimate a regional econometric input–output model (or REIM). REIMs were developed by Conway (1990) to model and analyze inter-industry trade over time (regionally and inter-regionally) when inter-industry sales are not regularly observed or published. These models have come to be used pervasively in analyzing and interpreting unexpected and non-linear changes in regional economies and associated impacts including environmental impacts (see, e.g. Donaghy, 2007, Tao et al., 2007). Typically, a REIM is constructed around a static table of inter-state and inter-industry sales coefficients (or elements of an input–output table indicating the portion of a dollar of input from one sector needed to produce a dollar of output of another sector) for a reference year. The dynamic time-series econometric model comprises a set of difference equations in macroeconomic variables—output, consumption, employment, investment, and government spending—on which time-series observations are regularly published and that account for the systematic deviations in sales patterns over time from the patterns in the benchmark year and systematic deviations in other economic variables whose values co-vary with the sales patterns. The model employed in the present study has been benchmarked following the approach developed in Jackson et al. (2006) and has been estimated with time-series data published by the U.S. Bureau of Economic analysis (BEA) and the U.S. Bureau of Labor Statistics (BLS) for the period 1977–2007, and is discussed in more detail in Brown-Steiner et al. (2015).

Once the parameters of a REIM have been estimated, time-series on inter-industry and inter-regional/inter-state sales coefficients can be extracted from the estimated model using the method of Israilevich et al. (1997) (Step 1 in Fig. 2) and, using published time-series on regional industry output levels, time series on inter-state and inter-industry commodity flows (in dollar amounts per year) can be derived (Step 2 in Fig. 2). Following the approach outlined above in the present study yields 2366 time-series of sales coefficients (13 sectors $\times$ 13 sectors $\times$ 13 states plus the RUS) and an equal number of time-series of commodity flows. For a more complete description of this REIM see Donaghy and Chen (2011) and Brown-Steiner et al. (2015).

The commodity flows (dollars per year) are next converted to freight tonnage per year using sector-specific conversion factors (in millions of constant year-2001 US dollars per kiloton of freight) taken from the 2007 Commodity Flow Survey (US DOT, 2010) (Table 1) (Step 3 in Fig. 2). Shipments between the various sectors can either be intrastate or interstate. Intrastate shipments (within a single state) are spatially allocated to each county in each state based on the county population (2007 US Census, released in 2010). Interstate shipments are allocated using a link-and-node model. This model creates a single node in each state at the center of the county with the highest population (Fig. 1) and connects these nodes with a great-circle path. The node for the Rest of the US (RUS) is specified as San Francisco County, California. Each individual node has a path to every other node (for a total of 105 links between 14 nodes including the RUS). We do not include changing population demographics over the time period of the study, although the population increased by roughly 10% during this historical period (Fig. 6). While the actual transportation system in the US is more complicated, this assumption broadly distributes transportation emissions over the MNUS. Advantages and disadvantages of our stylized transportation network, as well as the implications of the location of the RUS node are explored below.

For interstate freight the modal allocation of BC emissions (Step 4 in Fig. 2) distributes BC emissions from HDDV and rail transport ($BC_{HDDV+Rail}$) along the links connecting each state node by multiplying the length of the great-circle link by the total tons of freight shipped for each industry (to give ton-km). For intrastate shipments instead of great-circle links the freight total is multiplied by the square root of each state's surface area (km) to get each state's ton-km for each sector. Overall, and especially in and around cities and along transportation corridors, the interstate emissions are the dominant source of BC emissions.

The $BC_{HDDV+Rail}$ emissions depend on how freight is shipped. Here we neglect all BC transportation sources except those from HDDV and rail sources, as surface BC emissions are nearly all from HDDV and rail transportation modes (Uherek et al., 2010). We do not explicitly include emissions from 'super-emitters' (Bond et al., 2004). A time-varying emission factor of BC from HDDVs ($EF_{BC,HDDV}$) was obtained from default MOVES simulations (in grams of BC emitted per km) (see http://www.epa.gov/otaq/models/moves/). We assumed an average of 25 tons of freight per HDDV to get an estimate of the time-varying emissions from HDDV transport in

Table 1
Input-Output Sector description, abbreviations, commodity flow conversion in millions of dollars per kiloton of freight produced by a given sector (2007 Commodity Flow Survey, US DOT, 2010), and NAICS (North American Industry Classification System, http://www.census.gov/eos/www/naics/) code. A more detailed description of each sector can be found in the Supplemental Material.

Sector	Description	Abbreviations	Commodity flow conversion	NAICS code
1	Agriculture, forestry, fishing, and hunting	AGRICU	0.89	11
2	Mining	MINING	0.26	21
3	Construction	CONSTR	0.18	23
4	Food product manufacturing	FOODPM	1.40	311
5	Chemical manufacturing	CHEMMF	2.01	325
6	Primary metal manufacturing	PMETAL	1.18	331
7	Fabricated metal product manufacturing	FMETAL	0.06	332
8	Machinery manufacturing	MACHIN	9.42	333
9	Computer and electronic product manufacturing	COMPUT	22.02	3,34,335
10	Transportation Equipment	TREQPT	7.73	336
11	Other Non-durable Manufacturing	ONDRMF	1.56	312-316,322–324,326
12	Other Durable Manufacturing	ODRMFR	1.63	3,21,32,73,37,339
13	Transportation, Communication, Public Utilities, Services and Government Enterprises	GOVTEN	3.10	42,44,45,48,49,51 –56,61,62,71,72,81

Fig. 1. Study region. Black dots indicate location of each state's most populous county (2007 US Census, published in 2010) and are used as the nodes for the distribution of emissions. One additional county (San Francisco County, California) (not shown) serves as the node for the Rest of the US (RUS) region. The grey lines indicate counties within each state in the study region.

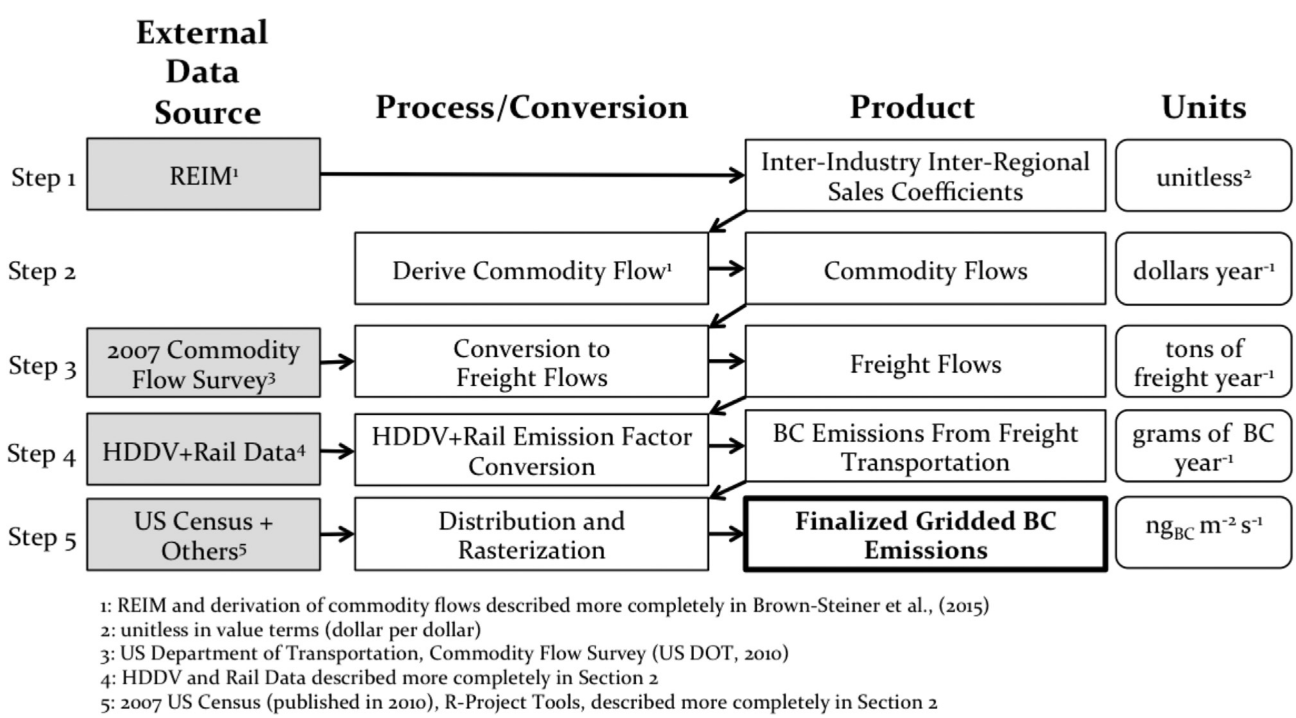

Fig. 2. Process Schematic for this paper. Section 2 describes in detail the central two columns of this Figure. The leftmost column indicates which external data sources were utilized in this study. The rightmost column gives the units of the product (3rd column).

grams of BC emitted per ton-km. While HDDV particulate matter emissions standards have decreased by over 99% during the historical period (US EPA, 2012b), the realized $EF_{BC,\ HDDV}$ has not decreased as dramatically as older model HDDVs are phased out of the active fleet. For rail, estimates of BC emissions is limited, both due to large uncertainties but also due to limited reporting from the rail industry. Rail standards for PM are on the order of 6.7–9.2 g per gallon of fuel (NESCAUM, 2006) and the EPA recommends a best-guess conversion of 400 ton-miles per gallon (US EPA, 2009). There are large uncertainties and a range of estimates for the BC fraction of PM (e.g. US EPA, 2012a), and we assume that BC makes up roughly 4% of the PM10 mass fraction (e.g. Handa et al., 2010; Pérez et al., 2010; Yttri et al., 2007) to get an estimate of BC emissions from rail (grams of BC emitted per ton-km for rail). We assume the emissions for rail transportation, due to the large uncertainties and lack of data availability, do not change over time. Overall our BC emissions factor from HDDVs start at 0.06 g of BC per ton-km in 1977 and decrease to 0.01 in 2007 while the BC emissions from rail remain at 0.01 g of BC per ton-km throughout the historical period.

Multiplying the emission factor (grams of BC emitted per ton-km) for a particular mode of transportation (i.e. HDDV or rail) times the percent transport by that mode over the calculated ton-km for interstate and interstate shipping gives the grams of $BC_{HDDV+Rail}$ emitted (per year). In 2007, HDDVs shipped roughly 69% and rail only 15% of the total tonnage of all commodity flows, while the remainder is transported via water, pipeline, air, and unknown methods (Margreta et al., 2009). We only include HDDV and rail shipments in this study. Since the 1970s, the distribution of freight among HDDVs and rail has remained largely unchanged although the volume has increased steadily (ICF, 2005). For interstate transportation we split the total ton-miles shipped for interstate transportation from 1980 to 2007 between HDDVs and rail with data from the US DOT (2015) (for 1977–1979 we use the 1980 values). There is preferential use of rail for heavy freight and long distances the rail mode transports more ton-miles (ICF, 2005). For intrastate transportation we give a slight preference for HDDVs (ton-miles are split 75% HDDVs and 25% rail which does not very over time) as HDDVs are preferentially utilized for short-haul shipments (US DOT, 2002). The data on HDDV and rail transportation splitting is mostly from national studies and is largely unavailable for state-by-state and commodity-by-commodity transport. Therefore we apply a single best-guess value over the entire region.

We next distribute both intrastate and interstate $BC_{HDDV+Rail}$ emissions spatially (nanograms of BC per year) by rasterizing data on each type of emission individually onto a 0.5° × 0.5° grid (to produce units of nanograms of BC cm^{-2} s^{-1}) and sum the two together to create gridded emissions (Step 5 in Fig. 2). Intrastate $BC_{HDDV+Rail}$ emissions are distributed across all counties in a given state using county-level population data as a proxy. Interstate $BC_{HDDV+Rail}$ emissions are allocated uniformly onto every grid cell that touches the great-circle freight flow paths connecting each node. This process utilized the following tools from the R-Project (http://www.R-Project.org/): maptools (Bivand and Lewin-Koh, 2013), raster (Hijmans and van Etten, 2013), ncdf (Pierce, 2014), sp (Pebesma and Bivand, 2005; Bivand et al., 2008), and classInt (Bivand, 2012). An evaluation of our data with the MACCity emission inventory is given in Section 3.

In order to conduct a preliminary analysis of inter-regional and inter-industry emissions from freight transportation and since this project is limited in spatial scope compared to global emissions inventories, the method described above has several limitations. First, our focus on 13 Midwestern and Northeastern states and the rest of the U.S. neglects freight transportation to and from Canada, which has traditionally been the largest destination for US exports and source of US imports until China recently topped Canada in US imports (Anderson and Coates, 2010). For example, automobiles and automobile parts cross the US-Canada border between the State of Michigan and the Province of Ontario multiple times during the production cycle (Anderson, 2012). We do not include these in our study, as the data on US-Canada transportation is not available in the BEA and BTS framework. Second, while choosing San Francisco County as the node for the RUS region adequately represents the east-west transportation corridors in the US, it neglects much of the north-south transportation corridors between the Midwest/Northeast region and the South/Southeast region (see Chun et al., 2012). Thus any freight transportation emissions between these two regions are instead distributed between the Midwest/Northeast and the West Coast, which is likely to lead to an overestimate of BC emissions in the MNUS region. Third, the large temporal and spatial differences in many of the parameters used in our conversion process (e.g. regional distributions of HDDV and rail technologies and infrastructure) have been simplified, although inevitably choices have to be made whether to focus on temporal resolution, spatial resolution, or more sophisticated structural representation of the underlying system. For instance, the Task Force on Hemispheric Transportation of Atmospheric Pollution, Version 2 (HTAP2) available at http://www.htap.org/and Janssens-Maenhout et al. (2015) has a much higher spatial resolution and global coverage, but only produces emissions for two years. This work focuses on the MNUS and largely examines the historical time-changing economic drivers forcing BC emissions. Finally, our use of great-circle pathways between nodes does not reflect the actual transportation corridors in the US highway system, although it does create stylized corridors, which we inspect and analyze below. In contrast to emissions inventories that distribute emissions via a population proxy (e.g. MACCity), which tend to overestimate exposure in and around urban centers, this study distributes the majority of emissions (the interstate emissions) via a stylized great-circle link-and-node network, which may lead to underestimates of BC exposure along the real-world interstate highways.

3. Comparison against standard existing BC emissions inventories

In this section we evaluate our $BC_{HDDV+Rail}$ emissions inventory projections and compare them to the MACCity emissions (available at http://accent.aero.jussieu.fr/MACC_metadata.php/) since the MACCity emissions have the most complete temporal coverage (1960–2010). The MACCity emissions are based on the ACCMIP emissions (available at http://accent.aero.jussieu.fr/ACCMIP_metadata.php/) for 1990 and 2000 and the RCP8.5 emissions for 2000 and 2010. The MACCity emissions give priority to regional emission inventories over global emissions inventories (Lamarque et al., 2010). The BC transportation emissions in ACCMIP, and thus the MACCity emissions, trace back to Bond et al. (2007), which themselves are an extension of BC inventories developed in Bond et al. (2004). The Bond et al. (2004) inventory is a global inventory using International Energy Agency (IEA) fuel consumption data and country-specific fuel, technology, and sector divisions in order to estimate BC emissions based on fuel type, and distributed emissions based on a population proxy. Thus we expect geographic differences between our results and MACCity results. We also expect some differences in the time-series of the regionally averaged emissions (e.g. due to US-Canada transportation).

The time-averaged (1977–2007) $BC_{HDDV+Rail}$ emissions from this study are compared against estimates from MACCity in Fig. 3. Although the MACCity inventory does not explicitly provide BC emissions for HDDV and Rail transport as calculated here, the corresponding emissions can be estimated by scaling the MACCity BC emissions in one of two different ways. One estimate (MACCity_LT) is based on scaling the MACCity land transportation BC emissions by 52% (US EPA, 2012a); the other estimate (MACCity_TOT) is based on scaling the total MACCity emissions by 28% (US EPA, 2012a). These fractions do not vary in time and so are rough

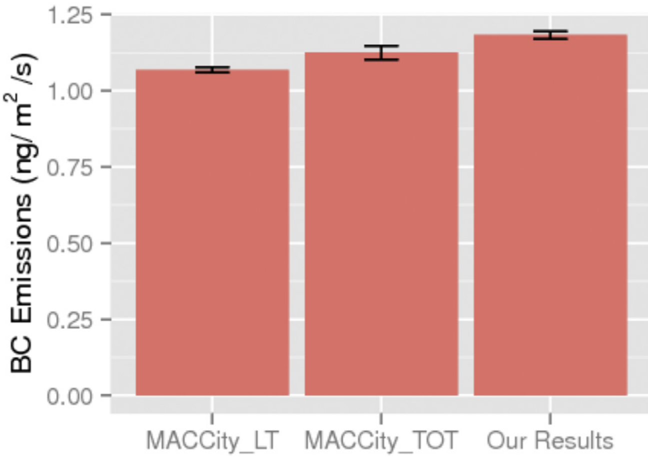

Fig. 3. Comparison of BC Emissions (ng/m^2/s) over this study region (Fig. 1) averaged from 1977 to 2007 from estimate for MACCity HDDV + Rail as 52% (US EPA, 2012a) of MACCity Land Transportation (MACCity_LT), estimate for MACCity HDDV + Rail as 28% (US EPA, 2012a) of MACCity Total (MACCity_TOT), and Our Results. Error bars cover the 95% confidence interval over 1977–2007.

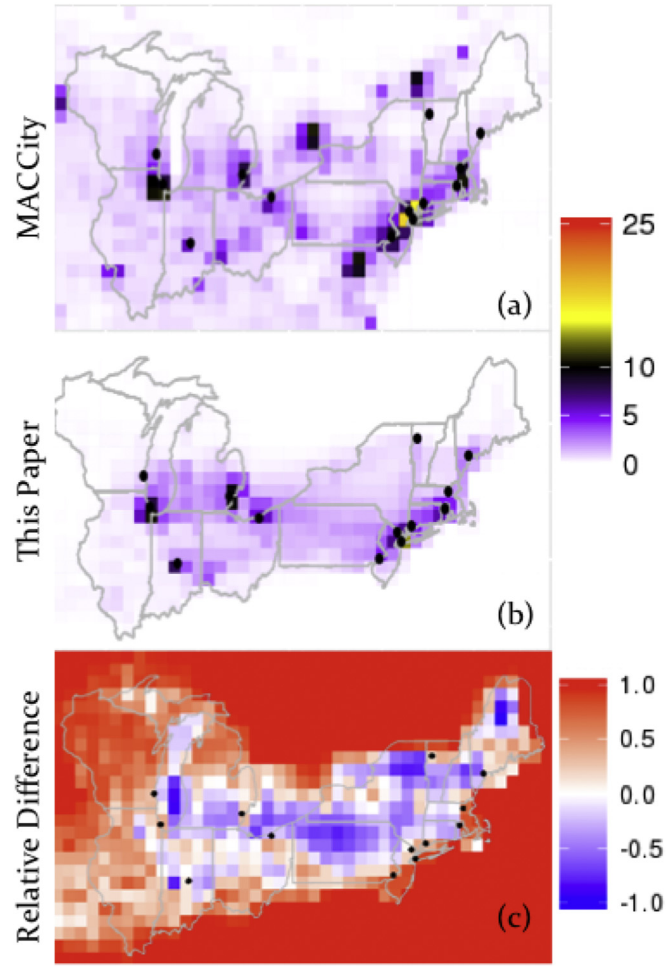

Fig. 4. BC transportation emissions (in ng/m^2/s) for 2007 from: (a) MACCity_TOT (see Fig. 3); (b) our study and (c) the Relative Difference between MACCity and our results; Relative Difference is defined as (MACCity − Our Results)/(MACCity + Our Results). Black dots mark the counties of highest population in each state (same as in Fig. 1) which serve as the nodes in our distribution process (Section 2). For (c) warm colors indicate MACCity is higher, cool colors indicate our emissions are higher. See text for descriptions of emissions sources and derivations.

approximations of the actual proportion of HDDV + Rail BC emissions. Our emissions are of comparable magnitude as the MACCity HDDV + Rail estimate with a 10–20% high bias compared to the MACCity estimates.

Fig. 4 compares the spatial distribution in the year 2007 of our BC emissions with the scaled estimate of the MACCity transportation BC emissions. For the MACCity BC emissions it can be seen that the emissions are distributed largely via a population proxy as BC emissions cluster around major urban areas. Our emissions are distributed both within urbanized regions and between urban regions along idealized great-circle transportation corridors. The largest differences between our emissions and the MACCity emissions are in areas where our results have distributed BC emissions between cities and the MACCity emissions have not. The relative difference (i.e. (MACCity − This Study)/(MACCity + This Study)) between the MACCity emissions and our emissions (Fig. 4c with warm colors indicating the MACCity emissions are greater and cool colors indicating our emissions are greater) is largest along our idealized east-west transportation corridor, where our BC emissions are ~50% higher that the MACCity emissions (e.g. over Northern Pennsylvania). This is due to our treatment of the stylized transportation network (see Section 2). At the edges of our region the relative difference between the MACCity emissions and our emissions approaches 1.0 as we do not simulate transportation patterns outside of the MNUS.

4. Results

Fig. 5 gives the total $BC_{HDDV+Rail}$ transportation emissions over our region divided into 13 sectors (Table 1) from 1977 to 2007, such that the sectors are classified according to which sector is doing the shipping (e.g. transportation emissions from a given sector to every other sector). Emissions from the actual manufacturing processes are not included in this study. These totals include both intrastate and interstate transportation emissions. The dominant sector contributing to $BC_{HDDV+Rail}$ emissions is FMETAL, representing 50–70% of total BC emissions throughout the historical period. The construction (CONSTR), other non-durable manufacturing (ONDRMF), and food product manufacturing (FOODPM) sectors contribute smaller but non-negligible $BC_{HDDV+Rail}$ emissions, with other sectors contributing less than 10% of the $BC_{HDDV+Rail}$ emissions. Both these FMETAL and CONSTR sectors are relatively small contributors to overall economic output (e.g. Tao et al., 2010), but both regularly transport heavy freight. BC emissions from FMETAL have two peaks in 1982 and 1997 with a steady decrease after 1997. The CONSTR sector shows little variation and only moderate growth in BC emissions throughout the historical period. We will examine individual sectors in more detail later in this section, but it is evident from Fig. 5 that the decline in the total BC emissions from 1997 to 2007 is largely explained by the decline in $BC_{HDDV+Rail}$ emissions from the FMETAL sector during that period.

An understanding of the historical BC emission trend requires an understanding of three underlying trends: population growth, GDP growth, and freight dynamics (in both tons and ton-miles of freight shipped). Fig. 6 plots these together both in real terms (top) and in the percent change per year (bottom) for the 13 states in our region. Between 1977 and 2007, the population, chained GDP (with the effects of inflation removed), tons shipped and ton-miles of freight all increased although the growth in total transported tonnage (Fig. 6b) is nearly double the growth in real GDP over the same period (Fig. 6a). The growth in total ton-miles fluctuated, sometimes growing at the same pace as the total tonnage shipped and

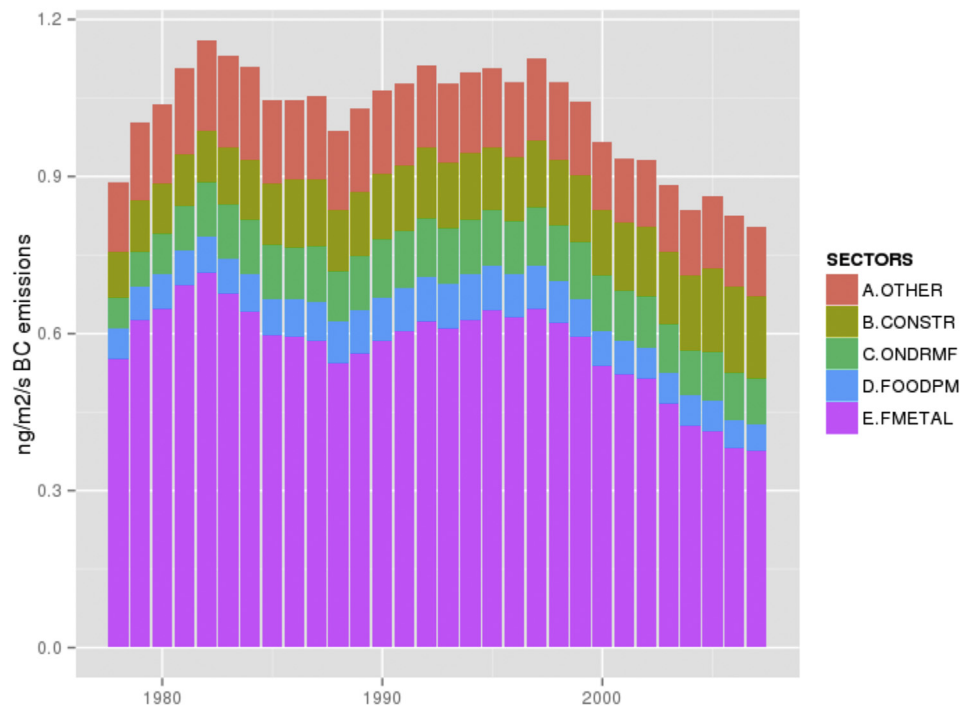

Fig. 5. Stacked Bar Plots of $BC_{HDDV+Rail}$ Emissions (in ng/m^2/s) over the entire study region from 1977 to 2007 by Sector. The OTHER sector contains the sum of the nine sectors not explicitly specified in the Figure.

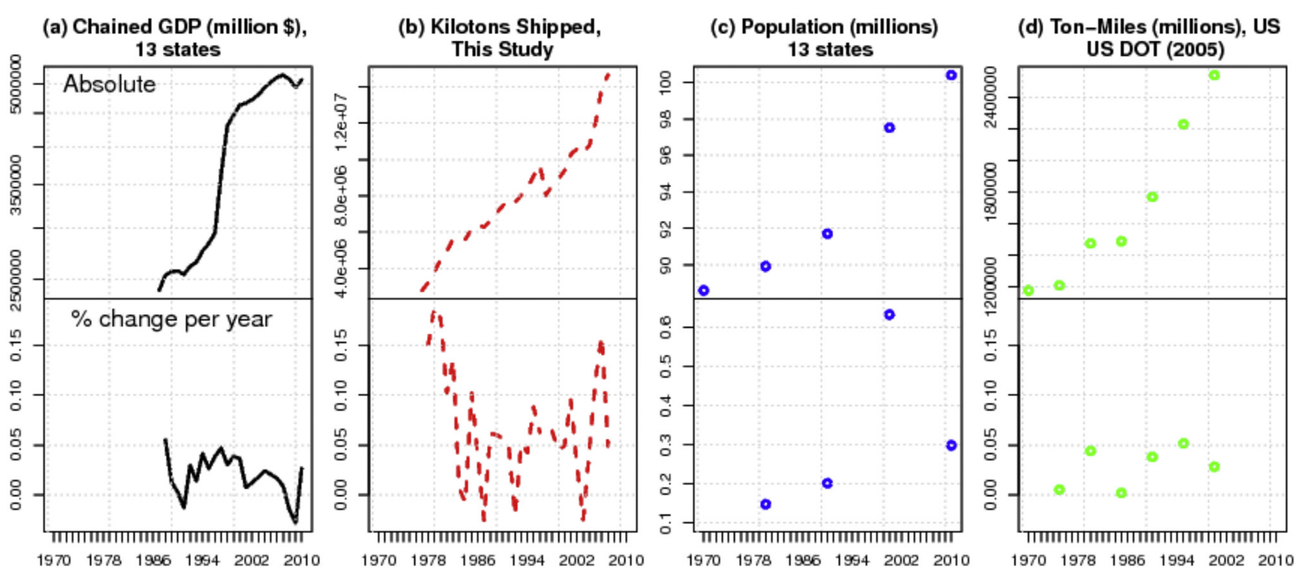

Fig. 6. Time series in absolute terms (top) and percent change per year (bottom) for (a) chained GDP (millions of dollars), which removes the growth in GDP due to inflation, and thus is a representation of the absolute growth in GDP, from http://www.bea.gov for the 13 states in this study. Note that the pre-1997 GDP is in chained 1997 dollars and post-1997 GDP is in chained 2009 dollars. GDP in 1997 is the average of the two databases. The jump in the chained GDP is the year 1997 is due to the change in methodology in calculating this term from the BTS database (see www.bea.gov/regional/docs/product); (b) kilotons of freight shipped (this study) for all regions; (c) population for the 13 states in our region in millions (from the 2007 US Census, published in 2010), please note that the vertical axis of this figure is different from the others; and (d) million ton-miles from HDDV and railroad transportation for the entire US ending in the year 2000 (US DOT, 2005) for comparison. As our transportation network is static, the ton-miles from this study would just be a scaled version of Fig. 6b.

sometimes growing at a smaller pace, or not growing at all (Fig. 6d). We will further analyze these factors when we examine trends in individual sectors below.

The methodology utilized to produce the region's $BC_{HDDV+Rail}$ emissions (Section 2) allows us to separate the competing influences of freight growth and decreasing EF_{BC}. In order to analyze these two factors we keep the EF_{BC} constant at 1977 levels while allowing changes in transportation changes to produce one set of BC emissions (EF^{const}), while we produce another set of BC emissions by keeping the transportation constant at 1977 levels while allowing the EF_{BC} changes to proceed as they have historically (TR^{const}). Under the TR^{const} case, the distribution of freight transportation between HDDV and rail is allowed to match historical levels, which results in slight increases in BC emissions during the beginning of the TR^{const} time series despite the general decrease in emission factors. By comparing these two trends we can explore the underlying causes of the change in $BC_{HDDV+Rail}$ emissions (Fig. 5).

The $BC_{HDDV+Rail}$ emissions, from both HDDVs and Rail (black), as well as the EF^{const} (red) and TR^{const} (blue) emissions are plotted together in Fig. 7 for four sectors (FMETAL, AGRICU, CONSTR, and MINING). Inspection of individual sectors in Fig. 7 show dramatic differences in both magnitude and temporal trend between sectors, and also allows us to explain some of the trends in total BC emissions from Fig. 6. We can classify the temporal trends of individual sectors into three categories based on the evolution of their freight volumes, which can be ascertained from the temporal emissions of BC assuming no change in the emission factor (EF^{const}, red line in Fig. 7). The first category, represented by the FMETAL sector in Fig. 7a, is *growth and plateau/decline*, in which continuous growth of freight volumes is noted until the mid-1990s after which freight volumes either level off or decline. Other sectors (not shown) that demonstrate similar temporal evolution are the FOODPM, COMPUT, and TREQPT sectors. The second category, represented in Fig. 7b by the AGRICU sector and 7c by the MINING sector, includes sectors in which freight flows have increased and decreased throughout the historic period, which we call *varying growth and decline*. Other sectors that follow this trend are the PMETAL and MACHIN sectors.

The third category contains all sectors that show *continued growth*, in which freight flows grow with little or no variation in the rate of growth throughout the historical period. Fig. 7d shows the CONSTR sector growth, which has been growing steadily over time. Other sectors that show this temporal trend are the FOODPM, CHEMMF, ONDRMF, ODRMFR, and GOVTEN sectors.

Increases in analyzed $BC_{HDDV+Rail}$ emissions between 1997 and 2007 when accounting for the temporal changes in emissions rates are noted for some of the *continued growth* sectors or the *varying growth sectors* if their rate of overall growth is greater than the concurrent decreases in EF_{BC} over the same period. These sectors include the CONSTR and GOVTEN sectors (both *continued growth*) and the MINING sector (with *varying growth and decline*). For all other sectors, $BC_{HDDV+Rail}$ emissions between 1977 and 2007 remained nearly unchanged (TOTAL, CHEMMF, ONDRMF, and ODRMFR) or declined (AGRICU, FOODPM, PMETAL, FMETAL, MACHIN, COMPUT, AND TREQPT). The total $BC_{HDDV+Rail}$ emissions largely follow FMETAL, although a higher variability is noted with a greater decline in BC emissions after 1997.

The spatial distribution of $BC_{HDDV+Rail}$ emissions is not expected to be uniform as we expect to see a “hollowing out” (Munroe et al., 2007) of certain industries as production centers become more centralized (Donaghy, 2012). Fig. 8 gives $BC_{HDDV+Rail}$ emissions averaged into a set of subregions for the MACCity inventory and our

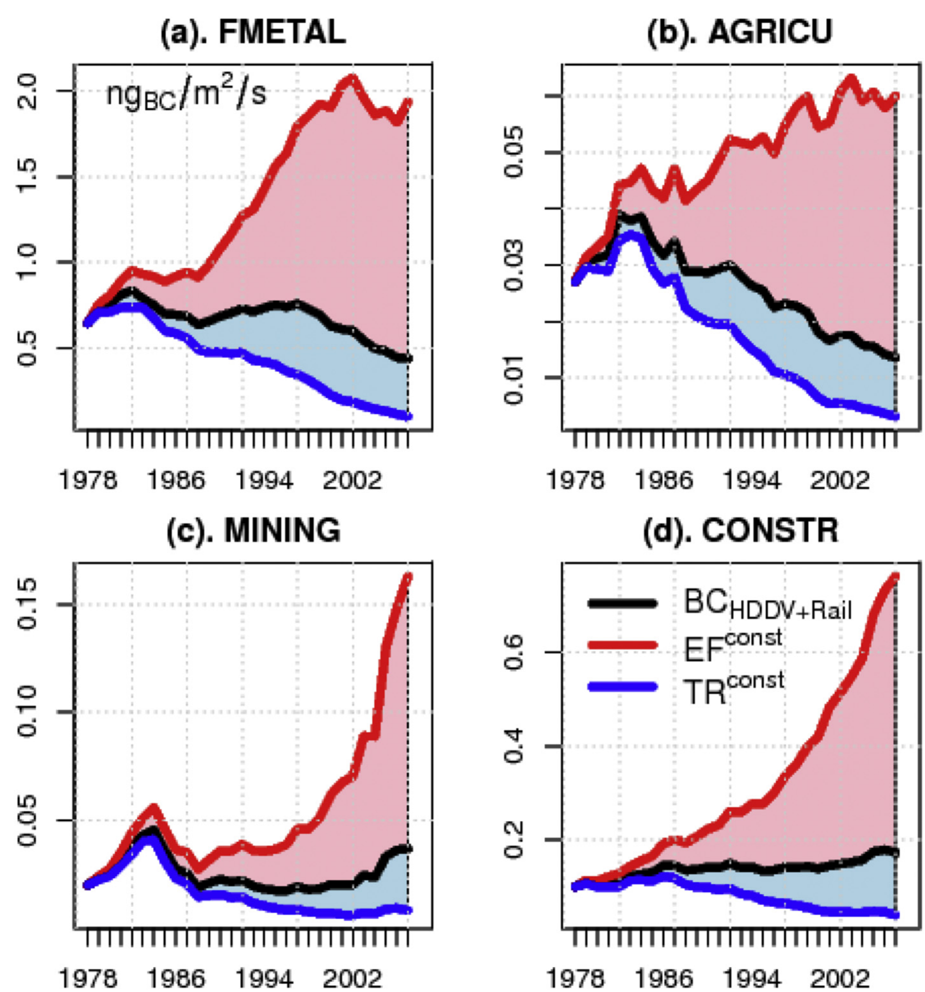

Fig. 7. Historical time series of $BC_{HDDV+Rail}$ emissions for four representative sectors (in $ng_{BC}/m^2/s$) in the study region (black), plus theoretical emissions if EF_{BC} is held constant at 1977 levels (EF^{const}, red) and if shipping/transportation volumes were held constant at 1977 levels (TR^{const}, blue). Note that the vertical axis is not the same for each sector. The four sectors represent different trends in temporal evolution of emissions assuming no change in emission factors including: (a) and (b) growth followed by a plateau or decline, (c) continued growth, and (d) varied growth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

results. Descriptions of the subregions are provided in the caption for Fig. 8, which provides emissions normalized by the maximum value in each dataset in order to examine the relative distribution among subregions independent of differences in total magnitude. Both inventories show BC emissions are highest in and around urban centers, in part because production centers are concentrated in these regions but also because both inventories, to varying degrees, use population as a proxy for the distribution of emissions. While MACCity has similar BC emissions in all non-urban subregions (the Midwestern and Northeastern Corridors and the Rural Subregion), our results show both higher emissions outside of urban subregions, particularly in the Northestern Corridor, and greater differentiation among subregions. Our results show that emissions in the Northeastern Corridor are of the same magnitude as emissions from the greater regions surrounding the six highest populated cities.

An examination of the regional differentiation of emissions from individual sectors, showing overall changes in $BC_{HDDV+Rail}$ is provided in Fig. 9. For both FMETAL and AGRICU (Fig. 9a,b), which represent the *growth and plateau/decline* category, the modest growth of freight volumes is insufficient to create increasing BC emissions, even in the major cities where our framework has the most growth. In contrast, the dramatic growth in freight volumes from the CONSTR sector, representative of the *continued growth* category causes increased BC emissions despite reductions in the EF_{BC} (Fig. 9c). Finally, the MINING sector (Fig. 9d), which represents the *varied growth* category, has two similar peaks in $BC_{HDDV+Rail}$ in 1982 and 2006, but we can see that the first peak is a result of modest growth in freight volumes at a time when EF_{BC} was relatively high, while the second peak is a result of very rapid growth in freight volumes at a time when EF_{BC} was relatively low.

5. Discussion and conclusion

In this paper we establish a framework to estimate BC emissions from heavy duty diesel vehicles (HDDVs) and rail transportation in

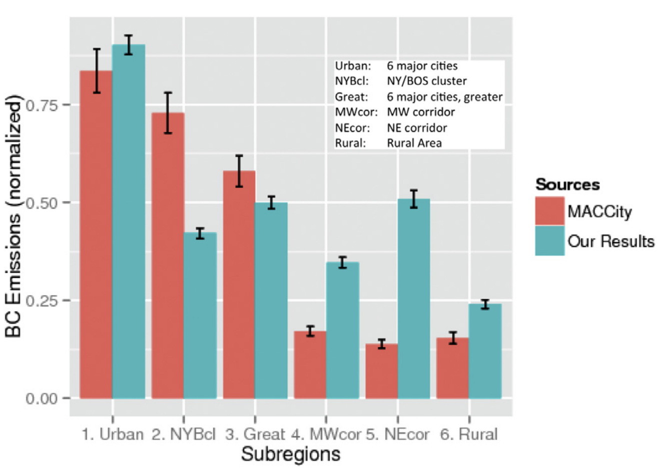

Fig. 8. $BC_{HDDV+Rail}$ Emissions from various sub regions for MACCity (red) and our results (blue). MACCity emissions are estimated as 28% of total anthropogenic emissions (MACCity_TOT). Subregions are defines as follows: urban is an average of 6 major cities (New York City, Boston, Cleveland, Detroit, Chicago and Indianapolis); NYBcl is the grid cells between the greater New York City and Boston regions but not the cities themselves; great is the greater urban areas, defined as the grid cells adjacent to (and including) the 6 major cities; MWCor and NEcor are the Midwestern Corridor (between Cleveland/Detroit and Chicago) and the Northeastern Corridor (between New York City/Boston and Cleveland), respectfully; and rural is a selection of rural gridcells in northern New York. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Midwestern and Northeastern US (MNUS) from 1977 to 2007 using available economic and derived shipment data. This work builds upon Donaghy and Chen (2011) and Brown-Steiner et al. (2015) in which a regional econometric input–output model (REIM) is developed, time series of freight flows derived, and BC transportation emissions ($BC_{HDDV+Rail}$) are distributed and gridded. This modeling approach allows the parsing of transportation emissions of BC by state and by sector, which in turn allows for a more detailed analysis of the overall trends in $BC_{HDDV+Rail}$ emissions. We isolate the influence on $BC_{HDDV+Rail}$ emissions of changes in the economic sector and the resulting change in demand for freight shipments and the influence of changes in the EF_{BC} due to increased regulatory efforts and technological and efficiency innovations. The $BC_{HDDV+Rail}$ emissions derived from our framework are comparable to other existing BC emissions inventories (Section 3). Note that throughout this section, unless otherwise specified, we refer to the total emissions ($BC_{HDDV+Rail}$) and not emissions under the cases of constant BC emission factor (EF^{const}) or constant 1977 freight transportation (TR^{const}).

While our analysis highlights many of the complex changes impacting $BC_{HDDV+Rail}$ emissions from transportation sources from 1977 to 2007, the scope of this study has required externalizing and simplifying many potentially important factors. We do not simulate international transportation here; we only simulate transportation between industries in the US while focusing on a limited number of states. Indeed by choosing to include only 13 states in the MNUS and using San Francisco, California as our node to represent the rest of the RUS we do not simulate transportation between the MNUS and the Southeastern US. We also simplify changes in the rail transportation fleet, in part since information on many of these changes is not publically available and remains highly uncertain. We also ignore the growth of intermodal transportation, which is where freight is transferred from one mode to another during the shipping process (Costello, 2013), or changes in HDDV and rail competition, which increased after the industry deregulation of the Motor Carrier Act of 1980 (Keebler, 2002; Costello, 2013). We do not include off-road emissions as the REIM does not estimate off-road emissions.

Here we ask again the two questions posed at the beginning of this paper: what are factors driving the changes in BC transportation emissions between 1977 and 2007, and what economic sectors dominate the BC emissions? For our first question our results show that $BC_{HDDV+Rail}$ emissions from freight transportation has overall exhibited little trend over the past 30 years, with the 2007 emissions only 10% lower than the 1977 emissions. The framework of this study allows us to explore in depth the concept that this overall trend in total BC from transportation emissions is a result of two competing and nearly counterbalancing factors: freight transportation has increased by a factor of around 5 while EF_{BC} has decreased by nearly 80% over the same historical time period. Without the increasingly stringent EF_{BC} regulations total BC emissions from transportation would be nearly five times as high as current levels (Fig. 7). Inversely, without the increased demand for freight transportation, $BC_{HDDV+Rail}$ emissions could be roughly one-quarter of current levels. The growth of freight transportation volume is not uniform among sectors, which show a variety of temporal changes over the historical period. In contrast, the change in EF_{BC} is assumed to be constant across sectors and states in our framework. Taken together, the decrease in the EF_{BC} has enabled increases in freight transportation volumes without resulting in increased BC emissions (e.g. US EPA, 2012a). The increase in transportation volumes is consistent with a transformation of the transportation sector as a part of an increasingly interconnected global economy that is dependent on just-in-time deliveries of both intermediate and finished commodities.

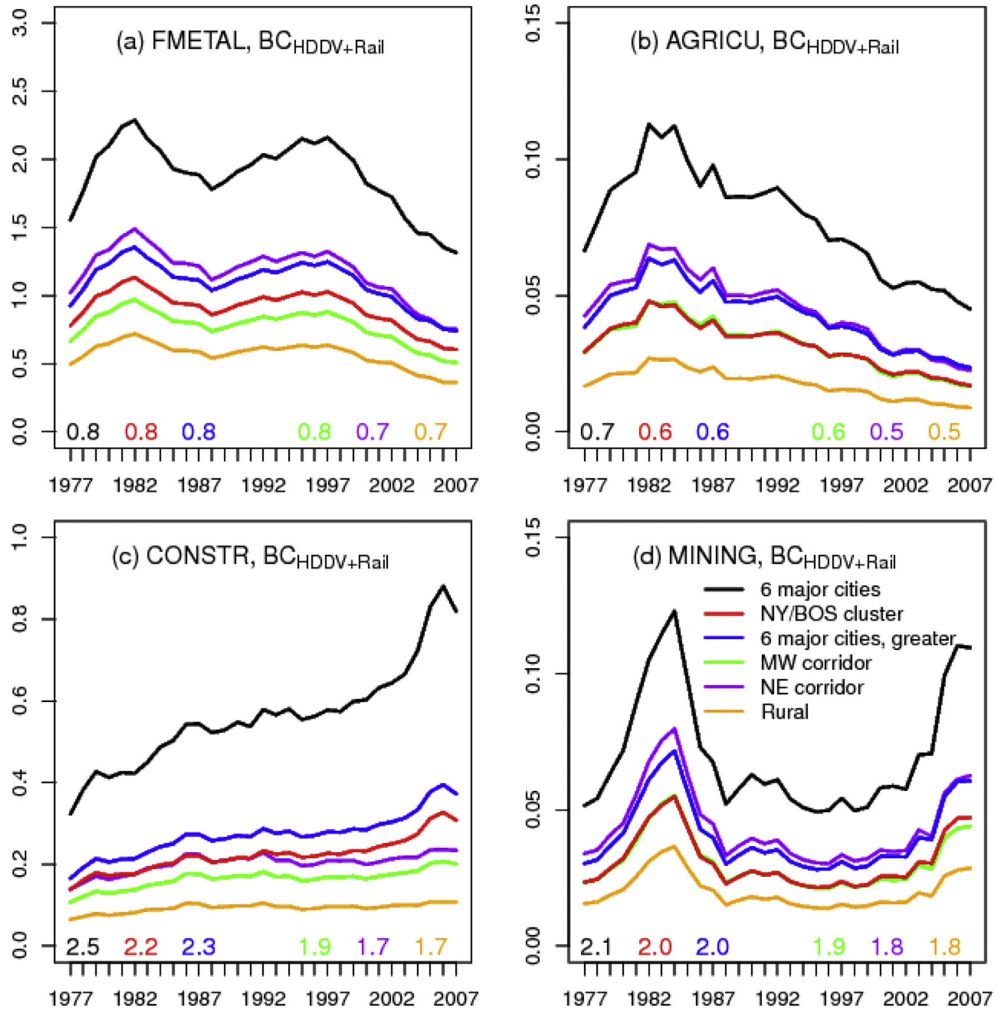

Fig. 9. $BC_{HDDV+Rail}$ Emissions ($ng_{BC}/m^2/s.$) from various subregions (descriptions in Fig. 8) for: (a) FMETAL, (b) AGRICU, (c) CONSTR, and (d) MINING. Sectors chosen as representatives of emission trend categories: FMETAL and AGRICU represent the *growth and plateau/decline* category, CONSTR represents the *continued growth* category, and MINING represents the *varied growth* category. Subregion definitions as in Fig. 8.

For our second question we find that throughout the historical period one industrial sector has dominated the $BC_{HDDV+Rail}$ emissions signal in the MNUS: fabricated metal (FMETAL). The FMETAL sector includes any industrial process, which make metal objects or performs finishing operations on metal objects. This sector, which emitted over half of the $BC_{HDDV+Rail}$ emissions in 1977 peaked in 1982 and 1996 but with emissions gradually decreasing from 1997 to 2007, represents roughly one-third of total BC transportation emissions in 2007 in the MNUS (Fig. 5). Tao et al. (2010), looking only at the Midwestern US, found a comparable drop in primary and fabricated metal manufacturing and attribute the drop to globalization (i.e. production of these goods requires less sophisticated technology and is readily replaced by importation).

The other sectors, which together make up about one-third of the total BC emissions, show dramatically different trends during the historical period. Some sectors show multiple maximums and minimums throughout the historical period. For example, the transportation emissions from the MINING sector peaked in the early 1980s, decreased until 2000, and peaked again by 2007 (Fig. 9d). Tao et al. (2010) also note this peak in the early 1980s and attribute it to the oil price spike as well as to a decline in domestic use of coal. Between 2000 and 2007, the number of US mining employees increased by 50% (US BEA, 2015).

We also find that changes in $BC_{HDDV+Rail}$ emissions are not uniform across the MNUS. In almost every sector, $BC_{HDDV+Rail}$ emissions have increased the most in and around urban centers (Fig. 9), which are serving as nodes in production networks and the freight distribution network. This is consistent with real world changes to the transportation network, which we discuss further below. Even in regions that have decreasing overall emissions, the decreases are usually smallest in and around urban centers (Fig. 9). In contrast, BC emissions from the MINING sector increased in all subregions, although with the largest increase noted in and around urban regions. Conversely, in sectors that show decreasing total $BC_{HDDV+Rail}$ emissions (such as the FMETAL and AGRICU sectors) the decreases are found largely outside of the urban centers (Fig. 9). Large decreases are noted in the stylized transportation corridors (i.e. MW and NE Corridors) while smaller decreases are noted in rural regions (Fig. 9).

The total magnitude of BC emissions in the MNUS region from our results is similar to other inventories (i.e. MACCity). Our results show fewer BC emissions in the areas surrounding urban centers while showing higher BC emissions in rural regions and along our stylized transportation corridors (Figs. 4 and 8). Relative to the population proxy methodology of many inventories, including MACCity, our methodology has redistributed a portion of the BC emissions away from urban areas and towards the transportation corridors. Although out transportation corridors are stylized, and do not represent the real-world interstate highways, these results highlight the need for BC emissions inventories to better represent the spatial distribution of transportation emissions, particularly if the emissions are to be used for the analysis of population weighted emissions or human health impact studies.

We ascribe the differences in sub-regional trends in BC emissions to regional changes in the producers of finished and semi-finished goods and the freight distribution system, which connects them, all under the influence of broader scale globalization. We caution, however, that we have used a stylized transportation network that cannot capture the subtleties of the actual changes. For example, there is growing evidence that the infrastructure and networks that make up the transportation sector between production centers are changing non-uniformly (Feenstra, 1998; Donaghy, 2007; Bowen, 2008; Rodrigue and Notteboom, 2010) and that production centers are shifting from city centers to suburban centers (Cidell, 2010). Many of these changes are not represented in our framework. Moreover, urban transportation trends in BC emissions are difficult to verify from atmospheric measurements. Overall, some urban centers have shown decreases in measured BC concentrations (e.g. Kirchstetter et al., 2008; US EPA, 2012a), while others show little or no trend, especially within the past decade (e.g. Allen, 2014). However, BC emissions in urban centers are from a variety of sources so attributing trends in atmospheric measurements to changes in transportation is difficult. For instance, decreasing BC in Boston from 2002 to 2005 is attributed to changes in the metro and school bus fleets, as well as changes to the highway infrastructure, while little trend in BC concentrations is noted from 2005 to 2012 (Allen, 2014). Additionally, diesel fleet composition has changed over time, and BC air quality in cities may be impacted more by off-road diesel vehicles than on-road diesel vehicles (e.g. Kirchstetter et al., 2008). Moreover, there is high spatial variability of BC concentrations within any given city (e.g. NYC Health, 2015) and each urban center contains a variety of different competing factors that can influence BC concentrations. Making direct comparisons between different urban centers is also difficult because data on traffic patterns within cities is limited (NCFRP, 2013), while studies that do exist have limited time horizons (e.g. Allen, 2014; NYC Health, 2015).

This study highlights some of the benefits and trade-offs inherent in regional-scale emissions inventories, especially in contrast to the benefits and trade-offs inherent in global emissions inventories. For instance, our limited spatial coverage allowed for a more detailed representation of the transportation network, here a stylized link-and-node network, but future work could create emissions along actual transportation corridors. In contrast, global inventories often distribute emissions via a population proxy. In addition, by including estimates of state and sector transportation data in this study we had the structure, but not the data availability or resources, to gather and include HDDV and rail modal distributions, details of freight loads, and emission factors on a sector-by-sector, state-by-state, and year-by-year basis. This type of research would be extremely valuable in understanding differences and potential biases in global versus regional emissions inventories.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.12.065.

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